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Energy, exergy and environmental analysis of cold thermal energy storage (CTES) systems

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ABSTRACT

As the air conditioning system is one of the largest contributors to electrical peak demand, the role of the cold thermal energy storage (CTES) system has become more significant in the past decade. The present paper has reviewed the studies conducted on the energy and exergy analysis of CTES systems with a special focus on ice thermal and chilled water storage systems as the most common types of CTES. However, choosing a proper CTES technique is mainly dependent on localized parameters such as the ambient temperature profile, electricity rate structure, and user's habit, which makes it quite difficult and complicated as it depends on many individual parameters. Therefore, it was found that energy and exergy analysis can help significantly for a better judgment. The review paper has shown that the exergetic efficiency analysis can show a more realistic picture than energy efficiency analysis. In addition, the environmental impact and the economic feasibility of these systems are also investigated. It was found that, based on the total exergy efficiency, the ice on coil (internal melt) is known as the most desirable CTES system.

Contents

1. Introduction

Cold thermal energy storage (CTES) technology is a concept of storing cold thermal energy in thermal reservoirs for later use. In the past century, when the mechanical cooling systems were not developed yet, people have taken advantage of natural cold thermal refrigeration systems such as caves, springs, ice and snow for many years. Nowadays, as the technology of mechanical refrigeration has been developed significantly, the necessity of employing the cold storage is more manifest. Generally, CTES systems are designed to store the cool energy in the thermal reservoirs for later usage [1]. In another point of view, the heat would be rejected from the thermal reservoirs during the charging period where the cooling demand is low [2]. The charging period of CTES systems is usually at night times where the outdoor temperature is comparatively lower than day times. Therefore, they will use less energy during charging period which improves the system efficiency [3]. It was also found that cool energy storage is significantly cheaper than equivalent electricity storing that produces the same amount of cooling [4]. Normally, by means of CTES systems the electricity consumption will shift from the daytimes to the night times.

Thermodynamic assessment evaluates the performance of the systems based on the first and second laws of thermodynamics.

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Nomenclature

AHU	air handling unit
CFC	chloro-fluoro-carbons
COP	coefficient of performance
CTES	cold thermal energy storage
CWS	chilled water storage
E	total energy
E	exergy
H	enthalpy
HCFC	hydro-chloro-fluoro-carbons
HVAC	heating, ventilating and air conditioning
ITS	ice thermal storage
PCM	phase change material
Q	heat transfer
S	entropy
T	temperature
TES	thermal energy storage
W	work

Greek letters

η	energy efficiency

Subscripts

Ch	charging
cond	condenser
Des	desired
evap	evaporator
In	input
Req	required

The thermodynamics assessments lead to the energy and exergy analysis. A powerful tool to evaluate the performance of a CTES system is exergy analysis on the basis of second law of thermodynamics. Exergy analysis is used to determine the exergy destruction sources and to improve the exergetic efficiency of the system. Exergy analysis is used to detect the irreversibilities of the CTES system which will be reviewed in the present study.

CTES systems are generally recommended if the maximum load of the system is considerably more than its average, the peak and off-peak electricity rates have a significant difference, or the available electric power is limited. There are certain requirements that a possible storage medium has to meet in order to be suitable for cold storage. The most common media for cool storage are ice, chilled water, eutectic salt phase change materials (PCM) [5,6] or paraffin [7]. The CTES systems might be employed to reserve the cooling energy in daily, weekly, yearly or even in the seasonal cycles [2].

Furthermore, the importance of demand reduction and demand management has made the energy storage technologies a valuable technique to act as a balance between supply and demand of energy. Shifting electric expenditure to off-peak hours has a major "Green" benefit of decreasing source energy usage and consequently reducing the amount of emission. Besides, producing off-peak electricity would consume less fuel that makes it cheaper [8]. However, they are not clearly categorized as green systems, as some believe that they are not green [9] and some categorized them as green technologies [10].

The present paper has reviewed the studies on the energy, exergy and environmental analysis of CTES system. It may be reported that to the best of authors' knowledge, there is no work on the review of CTES systems. Therefore, this review is expected to fill this gap.

2. CTES system background and applications

Brief and general information about the benefits and applications of different types of CTES systems is presented in this section. Fig. 1 illustrates the difference between the conventional air conditioning (AC) system and a system combined with CTES system. In the conventional system the chilled water distributed to the building through the distribution system. In this system the chiller works whenever the load is required in the building. However, in CTES system, the chilled water produced in the chiller, charges the cold thermal storage tank during off peak hours and distributed to the building during on-peak hours. In case that all of the required load reserved in the storage tank during night, the chiller will not work during on-peak hours (full storage strategy), on the other hand if part of the load is stored in the thermal reservoir during the night, the chiller would provide the rest, dashed line in Fig. 1(b), during the peak hours.

To encourage users to use the electricity at times where the utility operates at the low part load ratio, the normal working day is divided in to two parts of peak and off-peak hours were usually the electricity price is cheaper during the off-peak periods. It was found that with this strategy many of the users would shift their load to the off-peak hours and consequently, more peak capacities would be available for other uses, and off-peak capacity would be more fully used.

2.1. Different types of CTES systems

CTES systems are generally classified in three main categories of chilled water storage (CWS) systems, ice thermal storage (ITS) and eutectic salt TES systems [11]. Among them CWS and ITS systems are the most prevalent techniques that are widely used around the world. Some of the main differences between these storage technologies are tabulated in Table 1.

The sensible heat capacity of water is used in CWS systems. Water is cooled by mechanical cooler and stored in a thermal reservoir for later use. During the past decades different types of CWS system were designed and employed [14]. Some of the most common types of CWS systems are labyrinth, tank series, baffle, multiple tanks with an empty tank, thermally stratified and membrane systems [1]. Unlike the CWS system, ITS system uses the latent heat of fusion of water for storing the cold energy.

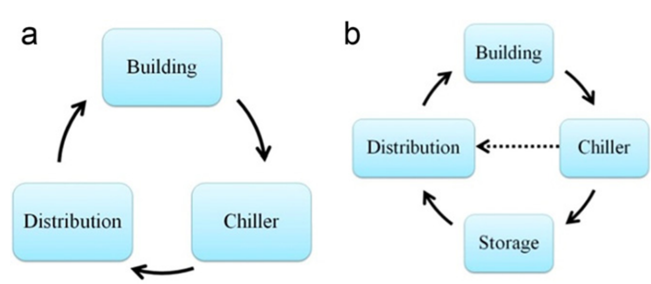

Fig. 1. The schematic illustration of (a) a conventional air conditioning system and (b) CTES system.

Table 1
Primary features of cold storage systems [11–13].

CTES type	Chiller type	Specific heat (kJ/kg K)	Latent heat of fusion (kJ/kg) [12]	Required tank volume (m^3/kW h)	Charging temperature (°C)	Discharge temperature (°C)	COP [13]
CWS	Standard water	4.2	–	0.129	4–6	1–4 above charging	5.0–6.0
ITS	Prepackage ice making	2	334	0.021	(−6)–(−3)	1–3	2.7–4.0
Eutectic salt	Standard water	–	80–250	0.048	4–6	9–10	5.0–6.0

Table 2
Comparison summery between two common storage media of ice and chilled water.

Ice	Chilled water
• Larger load capacity for given volume • Less space is required for delivering the same amount of cooling load • Lower maintenance is required • Lower storage temperature	• Compatible with available chiller for retrofit projects • The refrigeration design is the same as the non-storage system • Higher COP • Lower first cost

Table 3
Economical comparison between three most common storage media.

Storage media	Chiller cost (US$/t)	Storage tank (US$/t h)	Chiller charging (kW/t)
Water	200–300	30–100	0.6–0.7
Ice	200–500	50–70	0.85–1.4
PCM	200–300	100–150	0.6–0.7

Water, salt-water or small capsules of any PCM with solidification temperature lower than the available chilled water temperature are used as storage media [15]. Since the ITS system uses the latent heat of fusion it has an advantage of larger storage volume in comparison to the CWS system (Table 1). Assuming a reasonable temperature difference of 15 K between the water supply and return temperature for a liquid water storage system as well as for an ice storage system, it is obvious that ice storage required significantly lower storage space to preserve the same amount of cold energy ($Q_{ice} = Q_{water}$).

$$\frac{Q_{ice}}{Q_{water}} = \frac{V_{ice}\rho_{ice}(c_p\Delta T + h_{fg})}{V_{water}\rho_{water}c_p\Delta T} = \frac{V_{ice} \times 970(4.19 \times 15 + 334)}{V_{water} \times 1000(4.19 \times 15)} \Leftrightarrow V_{water} = 6.1 \times V_{ice} \quad (1)$$

The necessary volume for ice storage is about 1/5 to 1/8 of the volume of a CWS [10]. The ITS systems are generally categorized into ice harvesting [16], ice-on-coil [17–19], ice slurry [20,21] or encapsulated ITS systems [2,22]. They can be categorized as either static or dynamic ice making devises [23].

The information provided in Table 2, summarized some of the advantageous of two most common storage media. Comparison between different storage media from economical point of view is summarized in Table 3. The data has been provided by Roth et al. [15] and it shows that the initial cost of CWS system is the lowest but since it needs comparatively bigger storage tank, its storage construction cost is higher than ITS systems but is as much as PCM systems.

Additional information on different cool storage techniques is available in several sources such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) [24], the Electric Power Research Institute (EPRI) [10], the International Thermal Storage Advisory Council (ITSAC), the Thermal Storage Applications Research Center (TSARC), or cool storage vendors and manufacturers [25–30].

The operating strategy of CTES systems are generally divided into two major categories of full or partial storages. The partial storage strategy is classified into chiller priority or storage priority types [2]. In the full storage strategy, all of the required cooling loads are shifted to the off-peak hours and the chiller runs at full load during off peak hours and it charges the storage tanks. Unlike, in partial storage strategy, the mechanical cooling supplies part of the load where the rest is supplied from the storing tanks. Therefore, in partial strategy, the size of mechanical cooling is usually smaller than non-storage systems. This strategy is of interest of many designers as the total cost could be equal or even less than the non-storage system. Whenever the peak load occurred in a short period or there are small overlaps between peak energy hours and peak loads, the partial storage strategy is desired [31]. The partial storage strategy can be further categorized based on the selected operation strategies as the load leveling or demand limiting operations [24] or it can be categorized as storage priority and chiller priority [32] as well. Fig. 2, provides a schematic illustration for full storage, partial storage-load leveling and partial storage-demand limiting strategies.

2.2. CTES system applications

CTES systems have been employed in the industry for various applications to store the cool energy by using different types of thermal reservoirs [33]. The CTES systems are widely used in building applications such as office building [34], clinics [35], stores [36], Mosques [37] and schools [38,39]. They are also applied where preservation and transportation of temperature sensitive materials are involved [40,41]. The concept of using CTES systems for building applications were first introduced in the USA in the early 1980s. Statistics show that in the early 1990s around 2000 units of CTES systems were installed in the USA where 80 to 85% were ITS type, 10 to 15% CWS and the rest 5% were eutectic salt systems [42]. The available applications and their economic effects in Saudi Arabia have been studied by Hasnain et al. [43]. It was found that CTES systems can decrease around 30 to 40% of the peak cooling load in that region [44].

3. Energy and exergy analyses

The exergetic efficiency can be defined as the ratio of the output exergy to the input exergy. The input and output exergy of the biomass gasification process can be calculated directly based on the type of the reactants and products and their conditions. On the other hand, the output exergy can be considered as the difference between input exergy and the destructed exergy. The destructed exergy is the amount of exergy that is lost during the process due to the irriversibilities and it can be computed by applying the entropy analysis. The input, output and destructed exergy are shown schematically in Fig. 3.

In a CTES process, a cold came from the evaporator flows through the tank and transfers the heat from the tank to the refrigerating

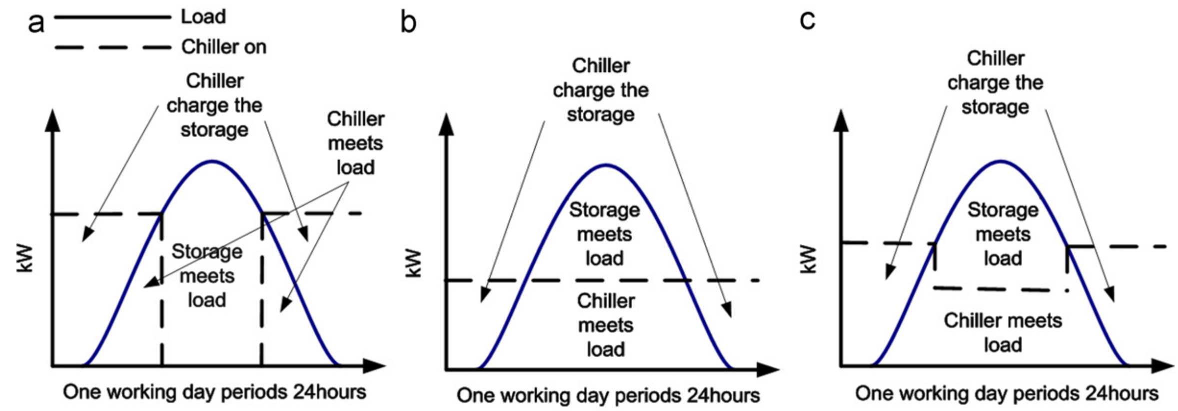

Fig. 2. Schematic drawing of different storage strategies. (a) full-storage, (b) partial-storage load-leveling and (c) partial-storage demand-limiting.

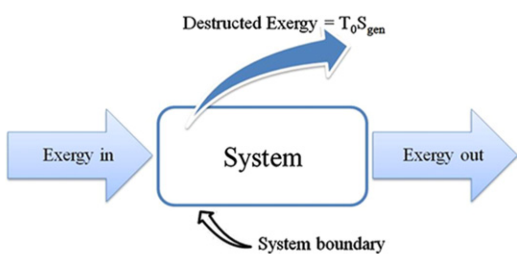

Fig. 3. Schematic illustration of exergy balance in a system.

cycle until the temperature of the tank drops to the inlet temperature. The stored cold energy will be kept in the tank for a period of time, which is called the storing process. A challenge arises in evaluating the energy and exergy efficiencies of this process because the efficiency is directly dependent on the process timing.

The input and output exergies, and the exergy balance equation of the three stages of charging, storage and discharging in CTES process are summarized in Table 4.

Determining the source of irriversibilities in the system with the aid of energy and exergy analysis, and decreasing the losses of the system would result in more efficient systems. The thermodynamic assessment of the systems can determine the losses of the process and consequently develop the optimization methods.

The mathematical formulation and performance analysis of a two-stage unit of the thermal energy storage system, during the charging and discharging stages were evaluated by Domanski et al. [45]. Applying the definition of entropy generation which was presented by Bejan [46], the exergy efficiency was calculated using Eq. (2):

$$\eta_{\text{second law}} = 1 - \frac{\text{total exergy loss during a cycle}}{\text{total exergy entering the system during a cycle}} \tag{2}$$

Investigating the effect of mass velocity on the exergy efficiency it was found that increasing the mass velocity would decrease the second law efficiency [45]. It was also pointed out that the best exergy efficiency would be obtained when the melting temperature of the downstream unit was closed to the ambient temperature.

The performance of four different ice TES case studies based on the first and second law of thermodynamics was assessed by MacPhee et al. [47]. The energy efficiency for all three stage of TES system was calculated using Eq. (3):

$$\eta = \frac{E_{des}}{E_{req}} \tag{3}$$

where, η is the energy efficiency, E_{des} is the desired Energy and E_{req} represents the required Energy. The energy balance equation during the charging stage was considered as it shown in Eq. (4):

$$Q_{evap} = Q_{cond} + Q_{loss,ch} - W_{in} \tag{4}$$

where, Q_{evap} is the evaporator heat transfer, Q_{cond} is the condenser heat transfer, $Q_{loss,ch}$ is the charging heat loss and W_{in} is the input work. The total amount of cool energy stored during the charging process was assumed to be equal to the evaporator heat transfer (Q_{evap}). Therefore the energy efficiency of the charging stage can be calculated by Eq. (5):

$$\eta = \frac{E_{des}}{E_{req}} = \frac{Q_{cond} - Q_{evap}}{W_{in}} \tag{5}$$

Some equations were presented [47] to compute the energy efficiency during the storage and discharging stage. The reported total energy efficiency for full storage is a little higher than the partial storage. The maximum energy efficiency was reported to be 99.02% for ice slurry storage system which was followed by ice on coil (internal melt) and encapsulated ice storage system with 98.92%.

The exergy analysis of a common kind of ITS system during charging, storage and discharging stages was investigated by MacPhee et al. [47]. The general exergy balance equation which was applied is shown in Eq. (6), it should be mentioned that E stands for exergy in this equation:

$$\Delta E_{sys} = E_{in} - E_{out} - E_{Q,ch} - I \tag{6}$$

The exergy efficiency was defined as the ratio of desired exergy to the required exergy. The variable of the presented case studies are similar to the study that was conducted by Dorgan et al. [2] and Wang et al. [21]. The total exergy efficiency of ice on coil (internal melt) was reported to be the maximum and was equal to 14.05% during full storage load and 13.90% during the partial storage load.

The exergy analysis of ice storage air conditioning system with heat pipes was carried out by Fang et al. [48]. The exergy analysis of enthalpy and heat were calculated based on Eqs. (7) and (8), respectively.

$$e = (h - h_a) - T_a(s - s_a) \tag{7}$$

$$e_q = \left(1 - \frac{T_a}{T}\right) q \tag{8}$$

where, e, h, s and T stand for exergy, enthalpy, entropy and temperature, respectively. Comparing the exergy efficiency of the ice storage air conditioning with heat pipe and the ice storage air conditioning with ice on coil, it was found that integrating heat

Table 4
The input and output exergies, and the exergy balance equation of different stages of CTES process.

Exergy	Charging	Storage	Discharging
Input exergy	Input work of chiller and the heat leakage to the storage tank	Heat leakage from outside to the storage tank	The heat from returned glycol solution from the building and the heat leakage from outside to the storage tank.
Output exergy	Heat transfer from condenser to the ambient	–	The cold energy transferred by the supply glycol solution to the building.
Exergy balance equation	$\Delta Ex_{sys,ch}=W_{in}-(Ex_{cond}-Ex_{leak,ch})-I_{ch}$	$\Delta Ex_{sys,st}=-Ex_{leak,st}-I_{st}$	$\Delta Ex_{sys,dc}=Ex_{in}-(Ex_{out}-Ex_{Q,dc})-I_{dc}$

Table 5
Key findings of a few case studies on application of CTES.

No	Building type	Location	Cool TES system	Key results.	Ref.
1	Office building	Texas (USA)	Ice-on-coil	Using a partial load storage strategy was resulted in smaller chiller size and smaller storage tank.	[34]
2	Dental clinic building	Texas (USA)	Ice harvester	The electric power consumption was shifted to the off-peak hour. System consumed about 29% more electrical energy in comparison with conventional air conditioning system.	[35]
3	Department store	London (UK)	Ice-on-coil (external melt)	The ITS system reduced the ongoing charges significantly.	[49]
4	Office building	Thailand	Ice-on-coil (internal melt)	The full storage strategy was able to reduce the electricity consumption cost 55% monthly. The total energy consumption reduced by 5%.	[50]
5	Clinic building	Kuwait	ITS	Among the different strategies, the "full load" could reduce the electricity consumption significantly.	[51]
6	Mosque of Makkah	Saudi Arabia	ITS	Full load storage strategy combined with incentive time structured rate reduced the electricity cost significantly.	[37]
7	High school building	Southeast Fort Collins	ITS combine with interactive direct digital control system	Energy cost reduced by $100,000 between 2004 and 2005.	[38]

pipe and ice storage air conditioning system would increase the efficiency by 9.55%. The exergy loss rate of the condenser was reported to be the highest. Summary of some the selected case studies on CTES is shown in Table 5.

4. Environmental effects study

Normally, CTES systems shift the power (electricity) consumption from on to off-peak or from daytimes to the nights when the ambient temperature is considerably lower. Therefore, they can significantly help the society to use the energy more efficiently and can role as a key to reduce the environmental pollutions. In a large scale view, as the CTES system reduces the energy consumption, the use of fossil fuels reduced and consequently the CO_2, SO_2, NO_x and CFC emissions reduced as well. In a smaller scale, employing CTES in buildings can also result to reduce the amount of combustion emissions from fuel-fired HVAC equipment and can reduce the emission of the harmful CFCs and HCFCs. As there is a significant temperature gradient across the Air Handling Unit (AHU)—usually smaller AHUs, less duct working and less electrical equipment are required. Moreover, as smaller or fewer chillers are used less CFCs and HCFC is required.

The research results from the UK [52] shows that by employing TES systems, the CO_2 emission can be reduced in the range of 14 to 46%. EPRI has also reported around 7% reduction in CO_2 emissions by using TES systems [53]. Rismanchi et al. [54] showed that employing ITS system with load levelling strategy can reduce the total energy usage by 4% compared to the conventional AC systems. They also found that this energy consumption reduction can lead to a significant emission reduction in range of 3000 to 60,000 t for the total system capacities of 352 and 7034 kW.

5. Future direction

The performance of the CTES can be improved based on the energy and exergy analysis. Further research and studies can be conducted on more environmentally friendly systems, which consume less electricity and produce less emission consequently. Integrating the CTES and renewable energy can be a method to achieve free pollutant cooling systems.

6. Concluding remarks

Based on the reviewed paper, it can be concluded that:

A. Generally, CTES systems are highly efficient in terms of energy evaluation. The energy efficiency varies from 90% to 98% based in different system configuration.
B. On the other hand, the exergy efficiencies are far less than energy efficiencies, with a maximum value of below 20%.
C. Comparing the energy efficiency and exergetic efficiency of the CTES systems it can be concluded that the exergetic evaluation provides a more realistic measure considering the irreversibilities and potential optimization of the storage/recovery process.
D. The electricity demand trend, the peak and off-peak hours, the electricity tariff rate and the country energy policy are the effective parameters were investigated in most studies.

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